

APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

TABLE-BASED SCHEDULER FOR FIFOs AND THE LIKE

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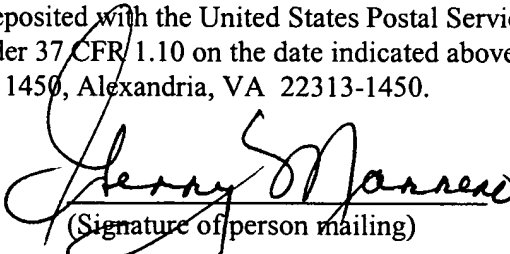

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TABLE-BASED SCHEDULER FOR FIFOs AND THE LIKE

TECHNICAL FIELD

The present invention relates to circuitry for computers and other data processing equipment and,
5 in particular, to schedulers for processing packets of data temporarily stored in a set of data packet storage devices such as first-in, first-out (FIFO) buffers.

BACKGROUND

In recent years, many communications systems have moved away from time-division multiplexed
10 (TDM) systems to higher-speed, and more-flexible, packet-based systems. These packet-based systems often include elements that switch and translate packets of data between numerous different communications protocols. This processing often relies on FIFO buffers to store and forward data packets. Often a different FIFO is used to buffer data from each independent communication channel in order to prevent blockage by packets from other channels. Since many high-speed packet protocols
15 support multiple independent data channels, the task of efficiently inserting and extracting packets into and out of these buffers can be challenging. This is because, with several FIFOs in the system, determining which FIFO to service next, and how to service it, may depend on several variables, including information on which FIFO is currently being serviced, as well as a scheduling algorithm that might depend on each of the other FIFO's status information (e.g., data available status) and the status of
20 the service process (e.g., extracting packets).

The function of determining which FIFO to service next is typically implemented using a finite state machine (FSM)-based device referred to as a FIFO scheduler. In programmable, hardware-based solutions, such as field-programmable gate arrays (FPGAs) and the like, FIFO schedulers are implemented using FSMs that use combinatorial feedback logic. Typically, the more FIFOs that need to
25 be scheduled and/or the more complicated the FIFO scheduling algorithm, the more complex the combinatorial feedback logic needed to implement the FSM of the FIFO scheduler. In order to keep the size and the execution time delay associated with FSM implementation and operation, respectively, at acceptable levels, either the number of FIFOs or the complexity of the FIFO scheduling algorithm is limited or both. This imposes undesirable constraints on such hardware-based solutions, often resulting
30 in less-than-optimal implementations.

SUMMARY

Problems in the prior art are addressed in accordance with the principles of the present invention by a scheduler for FIFOs (or other similar data packet storage devices) that relies on a look-up table (LUT) to determine which FIFO to service next, based on the current status of the FIFOs.

5 In one embodiment, the present invention is a scheduler for a plurality of packet storage devices, the scheduler comprising a memory device, a latch, and an extractor. The memory device is adapted to store a look-up table (LUT) that maps an input address to a LUT output, wherein the input address corresponds to current status of one or more of the packet storage devices, and the LUT output identifies a next packet storage device to select for service and whether the next packet storage device has data
10 available for service. The latch is adapted to store and forward the LUT output, and the extractor is adapted to receive (1) the forwarded LUT output from the latch and (2) service status information from the packet storage devices and to generate (1) a latch enable (LE) control signal that enables the latch to forward the LUT output and (2) a read enable (RE) control signal that identifies which one or more packet storage devices are to be serviced.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which like reference numerals identify similar or identical elements.

20 Fig. 1 shows a block diagram of a data packet processing system, according to one embodiment of the present invention in which the FIFO scheduler controls the operations of two FIFOs;

Fig. 2 shows a state diagram of the processing implemented by the extractor of Fig. 1 for an exemplary implementation of the extractor's finite state machine; and

Fig. 3 shows a block diagram of a data packet processing system according to another
25 embodiment of the present invention in which the FIFO scheduler controls the operations of four FIFOs.

DETAILED DESCRIPTION

Fig. 1 shows a block diagram of a data packet processing system **100**, according to one embodiment of the present invention. Processing system **100** has (a) a bank of two FIFO buffers
30 (FIFO_0 and FIFO_1) for storing packets of data, for example, for two different communication channels, and (b) FIFO scheduling circuitry (referred to as "the FIFO scheduler") for determining how and when data packets are to be removed from those FIFOs. In this embodiment, the FIFO scheduler includes memory **102** (e.g., a read-only memory (ROM) device), synchronous latch **104**, and extractor **106**. Unless otherwise indicated, all data lines in Fig. 1 correspond to one-bit signals.

Although not shown in Fig. 1, extractor **106**, synchronous latch **104**, and the two FIFOs are all synchronous to one clock signal. As used in this specification, a synchronous latch is any suitable device for storing and forwarding data based on that clock signal. In addition to the clock signal, latch **104** has two data inputs D0 and D1, a latch enable input LE, and two data outputs Q0 and Q1. When LE is enabled (e.g., high), the values of outputs Q0 and Q1 get updated to the values of inputs D0 and D1 at every cycle of the clock signal (e.g., at every clock rising edge). When LE is disabled, the values of outputs Q0 and Q1 are fixed and will not update with the clock signal, even though the values of inputs D0 and D1 will continue to update. Latch **104** can be implemented with a pair of flip-flops (i.e., one for each Di/Qi input/output pair), where each flip-flop also receives the clock signal and LE.

As shown in Fig. 1, each FIFO outputs a status bit (S0 from FIFO_0 and S1 from FIFO_1) that indicates whether or not the FIFO currently has a packet of data available for further processing (e.g., $S_i=1$ implies that FIFO_0 has at least one available data packet, while $S_i=0$ implies that FIFO_0 does not have at least one available data packet). (The exact process by which data is transmitted to and stored within the various FIFOs is not critical for purposes of the present invention.) In some implementations, a FIFO has a data packet available whenever it currently stores at least one complete data packet. In other implementations, a data packet is available only when the FIFO currently stores more than a specified threshold number of data packets, where that threshold is greater than zero.

These two FIFO status bits S0 and S1 are applied as inputs to memory **102**. Also applied as an input to memory **102** is bit Cp, which indicates which FIFO is currently selected for service (e.g., selected to have a data packet (if available) removed therefrom) (e.g., Cp=0 implies that FIFO_0 is currently selected for service, while Cp=1 implies that FIFO_1 is currently selected for service).

The three one-bit inputs (S0, S1, and Cp) are used to form a three-bit address for retrieving data from a look-up table stored within memory **102**. In particular, the LUT maps each three-bit input address to a two-bit LUT output consisting of bit Np and bit $SERV_N$. Bit Np identifies the next FIFO to be selected for service (e.g., Np=0 implies that FIFO_0 is to be selected for service next, while Np=1 implies that FIFO_1 is to be selected for service next), while bit $SERV_N$ indicates that the next FIFO to be selected for service has a data packet available (e.g., $SERV_N=1$ implies that the next FIFO to be selected for service has a data packet available, while $SERV_N=0$ implies that the next FIFO to be selected for service does not have a data packet available).

Latch **104** receives and stores Np and $SERV_N$ from memory **102**. In addition, latch **104** receives a one-bit latch enable (LE) control signal from extractor **106**. When LE=1, latch **104** forwards Np and $SERV_N$ as Cp and $SERV_C$, respectively. As described above, Cp identifies the FIFO currently selected for service. Analogous to $SERV_N$ described above, $SERV_C$ indicates whether the FIFO currently selected for service has a data packet available (e.g., $SERV_C=1$ implies that the FIFO currently selected for

service has a data packet available, while $SERV_C=0$ implies that the FIFO currently selected for service does not have a data packet available).

In addition to C_p being applied to memory **102**, C_p and $SERV_C$ are also applied to extractor **106**.

Also applied to extractor **106** is information from the FIFOs indicating the status of the service of the FIFOs. For example, in one implementation, the FIFOs transmit a two-bit FIFO service status signal $EOP[1:0]$ to extractor **106**, where each bit can be used to indicate the timing of the completion of the extraction of a data packet from the corresponding FIFO. For example, $EOP[0]=1$ indicates the timing of the completion of the extraction of a data packet from $FIFO_0$, while $EOP[1]=1$ indicates the timing of the completion of the extraction of a data packet from $FIFO_1$. Although EOP is shown as a multi-bit value, in an alternative implementation, EOP could be a single-bit value that is set to 1 to indicate the timing of the completion of the extraction of a data packet from the currently selected FIFO (whichever FIFO that may be).

The exact time that an EOP bit is set to 1 will depend on the particular type of FIFO used in the processing system. For example, for some types of FIFOs, $EOP[i]$ is set to 1 when the last byte of packet data is extracted from $FIFO_i$. For other types of FIFOs, $EOP[i]$ is set to 1 at other times, e.g., when the penultimate byte is extracted from $FIFO_i$. Depending on the particular type of FIFO is used, the timing for the rest of the processing system is designed accordingly.

Based on these inputs (C_p , $SERV_C$, $EOP[1:0]$), extractor **106** generates the one-bit LE control signal and a two-bit read enable control signal $RE[1:0]$. As described above, LE enables latch **104** to forward its stored data N_p and $SERV_N$ to update C_p and $SERV_C$, respectively. Each bit of RE indicates whether the corresponding FIFO is to be currently serviced (i.e., is to have a data packet removed therefrom). For example, $RE[0]=1$ implies that $FIFO_0$ should be serviced, while $RE[0]=0$ implies that $FIFO_0$ should not be serviced. Similarly, $RE[1]=1$ implies that $FIFO_1$ should be serviced, while $RE[1]=0$ implies that $FIFO_1$ should not be serviced. In a preferred implementation, no more than one bit of RE is set to 1 at any given time.

The exact details of when $FIFO_0$ and $FIFO_1$ get serviced depend on (1) the logic designed into extractor **106** and (2) the scheduling algorithm embodied in the LUT stored in memory **102**.

Fig. 2 shows a state diagram of the processing implemented by extractor **106** of Fig. 1 for an exemplary implementation of the extractor's FSM. According to this implementation, the extractor's FSM has two states: IDLE and EXTRACT.

The input to the IDLE state is $SERV_C$ (indicating whether the currently selected FIFO has data available). When the FSM is in the IDLE state and $SERV_C=0$ (indicating that the FIFO currently selected for service has no data available for service), extractor **106** sets the latch enable control signal LE to 1, and the FSM remains in the IDLE state. When the FSM is in the IDLE state and $SERV_C=1$

(indicating that the FIFO currently selected for service does have data available for service), the FSM transitions to the EXTRACT state.

The inputs to the EXTRACT state are C_p (indicating the FIFO currently selected for service), $SERV_C$ (indicating whether the currently selected FIFO has data available), and EOP (indicating whether extraction of a data packet from the FIFOs has just been completed). When the FSM is in the EXTRACT state and $EOP=1$ (indicating that the extraction of a data packet has just been completed), extractor 106 sets the latch enable control signal LE to 1 and updates the read enable control signal RE[1:0], and the FSM remains in the EXTRACT state. In particular, RE[1:0] is set such that the bit corresponding to the FIFO indicated by C_p is set to 1 and the bit corresponding to the other FIFO is set to 0. When the FSM is in the EXTRACT state and $SERV_C=0$ (indicating that the FIFO currently selected for service does not have data available for service), the FSM transitions to the IDLE state.

Because the FSM implemented by extractor 106 has only three different inputs (C_p , $SERV_C$, and EOP[1:0]) and two different states (IDLE and EXTRACT), the FSM can usually be efficiently implemented using combinatorial feedback logic. In alternative embodiments, the entire FSM could be implemented in software or in a combination of software and hardware, in either case with or without a look-up table (different from the LUT in memory 102).

Table I shows an exemplary look-up table for memory 102 of Fig. 1. In particular, Table I indicates how each three-bit input address (formed from S_0 , S_1 , and C_p) is mapped to each two-bit LUT output (corresponding to N_p and $SERV_N$).

TABLE I: EXEMPLARY LOOK-UP TABLE				
ROM Addresses			ROM Outputs	
C_p	S_1	S_0	N_p	$SERV_N$
0	0	0	0	0
0	0	1	0	1
0	1	0	1	1
0	1	1	1	1
1	0	0	1	0
1	0	1	0	1
1	1	0	1	1
1	1	1	0	1

Applying the FSM of Fig. 2 (initialized, e.g., into the IDLE state with $C_p=0$, $SERV_c=0$, $EOP[1:0]=(00)$, $RE[1:0]=(00)$, and $LE=0$) and the LUT of Table I to processing system 100 of Fig. 1 yields the following operational results for the system's FIFO scheduler. Assume that, at the beginning of processing, both FIFOs are empty (i.e., $S_0=0$ and $S_1=0$). In that case, with C_p (e.g., arbitrarily) initialized to 0, the first row of the LUT will apply, in which case, $N_p=0$ and $SERV_N=0$ (i.e., FIFO_0 is to be the next FIFO selected for service, but data is not available in that FIFO). In this case, with the FSM in the IDLE state, extractor 106 will set $LE=1$, enabling latch 104 to update C_p and $SERV_c$ based on N_p and $SERV_N$, respectively. In this case, at every execution cycle of extractor 106 (e.g., as driven by the clock signal (not shown)), the FSM will remain in the IDLE state and LE will remain set at 1.

Assume further that a data packet becomes available for processing in FIFO_0. In that case, S_0 will get set to 1, while C_p and S_1 remain at 0. In this case, according to the second row of the LUT, $N_p=0$ and $SERV_N=1$. With LE enabled, latch 104 will set $C_p=N_p=0$ and $SERV_c=SERV_N=1$. Setting $SERV_N=1$ will cause the FSM to transition to the EXTRACT state and extractor 106 to set $RE[1:0]$ to (01) and LE to 0. Setting $RE[1:0]$ to (01) enables FIFO_0 to read out a packet of data. When FIFO_0 finishes reading out that data packet, $EOP[0]$ is set to 1 and S_0 may or may not be reset to 0, depending on whether or not another packet entered FIFO_0. If another packet did not enter FIFO_0, then S_0 would be reset to 0. Resetting S_0 to 0 causes the input address for memory 102 to return to the first row of the LUT, which in turn causes $SERV_N$ to return to 0. Setting $EOP[0]$ to 1 causes LE to be set to 1, which in turn causes latch 104 to update C_p and $SERV_c$.

The processing of the FIFO scheduler of Fig. 1 proceeds in analogous manner for all of the different conditions embodied in the LUT of Table I.

In a classical round-robin scheduling algorithm, the FIFO scheduler considers each FIFO for service in a circular sequence (e.g., for N FIFOs, from FIFO_0 to FIFO_1 and so on to FIFO_($N-1$) before returning to FIFO_0 to repeat the sequence). If one or more FIFOs have data available after the processing of the currently selected FIFO has been completed (e.g., after a data packet has been extracted therefrom), then the round-robin FIFO scheduler will select the next FIFO in the round-robin sequence for service. If the FIFO that is next in the sequence does not have data available, then the FIFO scheduler skips over it to the next FIFO in the sequence, and so on, until a FIFO with data available is found, at which time that FIFO is selected for service. Prior-art implementations of such round-robin FIFO schedulers typically take at least one clock cycle to consider each different FIFO in the round-robin sequence, even those FIFOs that do not currently have data available for service.

The present invention can be used to implement a modified round-robin scheduling algorithm that does not waste clock cycles on FIFOs that do not currently have data available. In particular, because the scheduling algorithm is implemented using a look-up table that can simultaneously take into

account the current status all of the FIFOs, a FIFO scheduler of the present invention can be configured to skip over any FIFOs that do not currently have data available for service. If the FIFO that is currently being serviced still has data available after being serviced and no other FIFOs have data available, then the FIFO scheduler can continue to select the current FIFO for service. If no FIFOs have data available
5 after the currently selected FIFO is serviced, then the FIFO scheduler might continue to select that same FIFO but it will not be serviced. This can continue until a FIFO has data available for service. In a preferred implementation, whenever at least one FIFO has data available, another FIFO having data available will be selected for service within one clock cycle of the end of the servicing of the previously selected FIFO (including those situations where the same FIFO is re-selected).

10 Because FIFO scheduling of the present invention is driven by a look-up table, a FIFO scheduler can be configured to operate based on any suitable scheduling algorithm employed to determine which FIFO to service next. Round-robin sequences are just one possible type of FIFO scheduling algorithm. Those skilled in the art will understand that many other possible FIFO scheduling algorithms exist. Depending on the implementation, the LUT for a particular FIFO scheduling algorithm can be generated
15 off line, external to the FIFO scheduler, and then loaded into the scheduler's memory for use during on-line data processing.

Moreover, because FIFO scheduling is based on a LUT, the execution time of the scheduling process is independent of the complexity of the scheduling algorithm. In other words, the time that it takes to execute the FIFO scheduler is the same when the LUT corresponds to a relatively simple
20 scheduling algorithm (e.g., where the next FIFO selected depends on only a subset of the statuses of the other FIFOs) as when the LUT corresponds to a relatively complex scheduling algorithm (e.g., where the next FIFO selected depends on the statuses of all of the FIFOs).

Compared to the prior-art implementations, the present invention can be efficiently implemented for any desired number of FIFOs, with the primary limitation being the size of the memory needed to
25 store the corresponding LUT. As such, the present invention supports the implementation of more complex scheduling algorithms for greater numbers of FIFOs more efficiently than conventional implementations in which the scheduling algorithm is implemented entirely in an FSM with combinatorial feedback logic (or even in software).

In the implementation described for processing system 100 of Fig. 1, each instance of FIFO
30 service involved the removal of a single data packet from a single FIFO. In alternative implementations, FIFO service could involve the removal of more than one data packet from the currently selected FIFO i . In this case, the extractor could be implemented to look for $EOP[i]=1$ more than once, before determining that FIFO service had been completed. Moreover, each instance of FIFO service could involve the removal of data packets from more than one FIFO. For example, more than one bit in the control signal

RE could be set to 1, and the FIFO bank could determine the sequence of processing those multiple FIFOs. Such processing could be supported by logic implemented within extractor **106**.

Depending on the particular application, the data packets may be of fixed or variable length. For fixed-length data packets, the EOP signal becomes optional. In a particular, an extractor could be implemented with an internal timer that counts an appropriate number of clock cycles after re-asserting the read enable signal RE to determine, in an open-loop manner, when the currently selected FIFO has completed the extraction of a data packet.

Although the present invention has been described in the context of data processing applications that schedule service for data packets stored in storage devices implemented as FIFOs, the present invention is not so limited. For example, the data storage devices can be implemented using data structures other than FIFOs. Moreover, a data processing application could involve the scheduling of service for packet-based communication buses or other types of data pipes as the "data storage" devices.

Although memory device **102** of Fig. 1 has been described as being a read-only memory, the present invention can be implemented using any suitable type of memory device for storing the desired look-up table, including suitable random-access memory (RAM) devices.

Fig. 3 shows a block diagram of a data packet processing system **300** having a FIFO scheduler that controls the operations of four FIFOs (FIFO_0 to FIFO_3). Processing system **300** is based on the principles of processing system **100** of Fig. 1, analogously extended from the two FIFOs of Fig. 1 to the four FIFOs of Fig. 3. In this case, the LUT stored in memory **302** relies on six-bit input addresses corresponding to S0, S1, S2, S3, and Cp[1:0], where S_i indicates whether FIFO i has data available for service, and Cp[1:0] is a two-bit code that identifies which FIFO is currently selected for service (e.g., Cp[1:0]=(00) indicates the FIFO 0 is selected, Cp[1:0]=(01) indicates the FIFO 1 is selected, and so on). The LUT generates three-bit outputs corresponding to Np[1:0] (which is analogous to Cp[1:0]) and $SERV_N$ (which is the same as in Fig. 1), and latch **304** updates Cp[1:0] and $SERV_C$ (which is the same as in Fig. 1). Like extractor **106** of Fig. 1, extractor **306** implements a two-state FSM like that shown in Fig. 2, except that extractor **306** receives a four-bit end-of-packet signal EOP[3:0] from the four FIFOs and generates a four-bit read enable control signal RE[3:0] for the four FIFOs.

A comparison of the systems of Figs. 1 and 4 indicates that the present invention can be extended to larger and larger numbers of FIFOs simply by increasing the sizes of (1) the memory used to store the scheduling algorithm's LUT and (2) the latch used to update certain parameters. As described previously, for a given number of FIFOs, the FIFO scheduler can implement any desired scheduling algorithm of any desired level of complexity without impacting execution time.

Because the FIFO scheduler is based on a look-up table, the memory device (if reprogrammable) can be reconfigured to change the scheduling algorithm. In particular, the scheduling algorithm and/or

the number of FIFOs to be serviced can be changed simply by changing (e.g., rewriting) the LUT stored in the memory. None of the rest of the hardware needs to be changed, including the latch and the extractor. Moreover, the same hardware design can be used for different instances of the circuitry that support different applications (e.g., involving different scheduling algorithms or different numbers of FIFOs).

This flexibility of the present invention is especially advantageous in situations in which the processing system is implemented in programmable processors such as FPGAs. In conventional FPGA implementations in which the FIFO scheduler is implemented using an FSM with combinatorial feedback logic, the number of FIFOs and/or the complexity of scheduling algorithm have been limited by the available circuit layout space, routing resources, logic placement, and applicable timing constraints. Moreover, changing the scheduling algorithm would involve changing the design of the combinatorial feedback logic used to implement the FIFO scheduler. This in turn would often require redesign of much if not all of the FPGA programming, including possibly having to redo the placement and routing for the entire FPGA circuit.

Although the present invention has been described in the context of FPGAs, those skilled in the art will understand that the present invention can be implemented in the context of other types of devices, such as, without limitation, programmable logic devices (PLDs), mask-programmable gate arrays (MPGAs), simple programmable logic device (SPLDs), and complex programmable logic devices (CPLDs), and even devices such as application-specific integrated circuits (ASICs).

The present invention may be implemented as circuit-based processes, including possible implementation as a single integrated circuit (such as an ASIC or an FPGA), a multi-chip module, a single card, or a multi-card circuit pack. As would be apparent to one skilled in the art, various functions of circuit elements may also be implemented as processing blocks in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.

It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims.

Although the elements in the following method claims, if any, are recited in a particular sequence with corresponding labeling, unless the claim recitations otherwise imply a particular sequence for implementing some or all of those elements, those elements are not necessarily intended to be limited to being implemented in that particular sequence.